A Novel Sensing Tether for Rovers

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Luna has extended the length of its fiber optic shape sensing technology out to a continuous, high-fidelity measurement of a 100-meter sensor, creating a novel concept for a self-monitoring tether for robotic exploration. This tether is capable of measuring its own tension, curvature, and full 3-D shape along its entire length as it is deployed by a robotic rover. Using Optical Frequency Domain Reflectometry (OFDR) and the Rayleigh scatter signature to sense the state of a customized multicore optical fiber, the new technology is lightweight, compact, and immune to electromagnetic interference. Results are presented from tests with a 50-meter tether on the Axel Rover at JPL's Mars Yard testing ground.

I. Nomenclature

Axel	=	A two-wheeled rover capable of tethered rappelling across steep-terrain topographies
OFDR	=	Optical Frequency Domain Reflectometry
TLS	=	Tunable Laser Source
με	=	Microstrain
N	=	Newtons
m	=	Meters
JPL	=	Jet Propulsion Laboratory
NASA	=	National Aeronautics and Space Administration

II. Introduction

With the Curiosity rover currently exploring Mars, NASA is continuing its work of expanding our knowledge of our planetary neighbors. While Curiosity, and its older cousins Spirit and Opportunity, have exceeded all expectations and continue to provide crucial scientific information, future missions are anticipated to require greater mobility to reach highly-prized science targets that lie in challenging terrain. Conducting science on these hard-to-reach sites would advance our scientific knowledge of their composition and formation processes, thus furthering our understanding of the solar system. On these missions, rovers will encounter difficult terrain as they navigate to interesting geological features for *in situ* measurements and physical sample collection. These future rovers must be more rugged, and have more dexterous robotic capabilities, than the rovers of today.

One option is to have smaller tethered marsupial rovers, such as JPL's Axel rover[1], that can be deployed from the primary rover or base station to navigate into craters, over cliffs or across dunes. In addition to providing power and decreasing the need for onboard electronics, the tether can be used to support the rover as it navigates steep slopes, to pull the rover out of loose soil, or to guide the rover back to the base station. Axel's capabilities have been demonstrated over slopes in excess of 80 degrees when it uses its tether for support. Unfortunately, the tether can also be a liability. As the rover traverses away from the base station, the tether is paid out by the rover to minimize

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rubbing across the terrain. However, it will be pressed against the rugged surface, it could get pinched between rocks or it could get snagged between a rock an the terrain. The rappelling motion of the rover will create high-stress concentration points along the tether. If the tether gets damaged, the rover may lose power and communication, thus limiting the lifespan of the rover to the last charge, which would end the mission prematurely. Therefore, monitoring the health of the tether throughout the traverse would be important to guide the rover toward paths that would minimize high-stress concentration points along its length, thus alleviating risks that could sever power, communication or mechanical support. A system that monitors the tension at one or both ends of the tether may detect snags and assist in guiding robot navigation, but such a system cannot account for the path of the cable, detect the location of a corner or pinch point, or tell when the robot has gone over a hill or a cliff. Knowledge of the tension along the entire length of the fiber, as well as the tether's distributed curvature and approximate shape can provide critical information about the terrain between the robot and the base rover, identifying cliff edges, twists and turns, and sharp rocks. Such a tether would be beneficial to a wide class of robots, from Axel to more miniature crawlers, swimmers, projectiles, and sample gatherers.

Luna has developed and, with assistance from JPL, tested a prototype tether that uses a specialty multicore optical fiber and Optical Frequency Domain Reflectometry (OFDR) technology that measures the fiber's Rayleigh scatter signature to monitor its tension and curvature distributed along its length. With laboratory testing to more than 100 m and field testing at more than 50 m, this is the first demonstration of continuous, high resolution curvature and tension measurements over long lengths. In addition, the specialty fiber is also able to provide a communication link between the rover and the base station. Testing with the Axel Rover showed the tether's ability to identify the anchor point, a pinch point, and the point where the tether entered Axel's winding spool, without adding significant mass to the tether or the rover. A laser-based interrogator system sits at the proximial end of the tether, and can be incorporated into a base station or larger robot that supports the rover on its mission. The sensing tether system presented in this paper turns passive tethers into an active sensing device that is useful for navigation and rover control.

III. Measurement Approach

A. Distributed Sensing using Multicore Optical Fiber

The prototype sensing tether technology resembles a traditional tether cable except that sensing and communication are provided by a specialty fiber optic sensor that has been incorporated into the cable, located at the neutral axis. The distributed strain, axial twist, and curvature along the length of the sensing fiber is used to determine the cable's tension and curvature. The sensing fiber contains multiple light-guiding cores within one shared cladding structure, making it possible to monitor its strain, axial twist, and curvature through a precision measurement of distributed strain along the fiber's central core and spiraling three outer cores[2]. Members of the "triad" of outer cores are spaced at 120˚ azimuths, at a fixed radius from the center core.

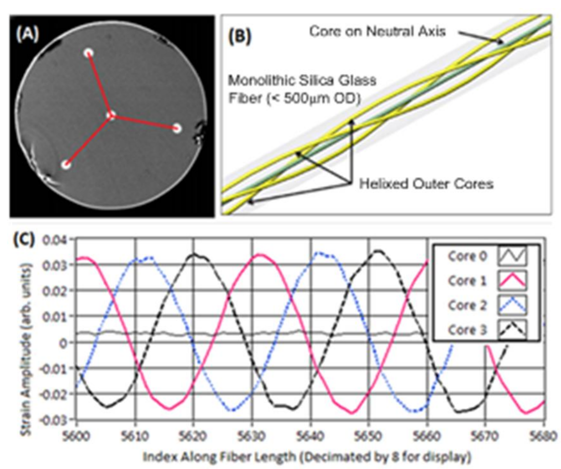

Figure 1: (A) SEM micrograph of shape sensing fiber, sensing cores in red; (B) Illustration of helical cores along length of fiber; (C) Typical four-core strain response to external curvature.

Under curvature, each of the outer cores experiences alternating states of tension and compression on its helical path through the bend. The center core, which is precisely located in the center of the sensing fiber, experiences negligible first-order strain. The three outer cores exhibit sinusoidal strain responses, each 120˚ out of phase with the others. By comparing the amplitude and phase of these three strain curves, one can determine the applied bend radius and its direction relative to the fiber's coordinate system.

Under twist, all of the three outer cores experience a common-mode strain, while the center core again experiences negligible strain. If the fiber is twisted in the direction of the helix, a tensile strain is applied to the triad of outer cores. A twist in the opposite direction places the outer cores in compression. By observing the magnitude of the common-mode strain signal, one can determine the distributed state of twist along the length of the sensing fiber.

Under tensile strain or a large temperature change, all four cores experience a common-mode strain. The center core is used as a reference to measure for tensile strain and temperature changes in the shape sensing fiber, and to subtract these signals from the outer cores as they measure curvature and twist.

B. Strain Sensing Using Rayleigh Scatter

To accurately measure the distributed strain along the length of each of the four optical cores in the sensing fiber, Luna relies on a customized implementation of Optical Frequency Domain Reflectometry (OFDR), providing very high spatial resolution, giving the most complete picture of any of the viable distributed fiber optic sensing techniques. Using state-of-the-art techniques, Luna's OFDR system can achieve ± 1.6 $\mu\varepsilon$ resolution over 1.5 mm gage width[3] and better than 50 micrometer spatial resolution[4]. A basic OFDR network is shown in Figure 2.

When interrogated by a laser light source, the Rayleigh backscatter of an optical fiber core produces a random but stable spectral pattern, unique to each specific fiber core, which is recorded by the instrument. Figure 3(a) shows the reflected spectrum of a segment of scatter from a single core of the multicore optical fiber. Applied strain, induced by a change in the curvature, tension, or twist of the sensing fiber, shifts the reflected spectrum of the scatter in the fiber at the location it is applied. Finding the frequency shift of the scatter spectrum can be accomplished by performing a cross-correlation of the scatter spectrum from a measurement data set with that from a reference data set taken with the fiber under test in some nominal strain state. Figure 3(b) shows the cross-correlation of a reference scatter spectrum with one that was perturbed by a strain change. The correlation peak is shifted from center by a frequency shift resulting from the strain change.

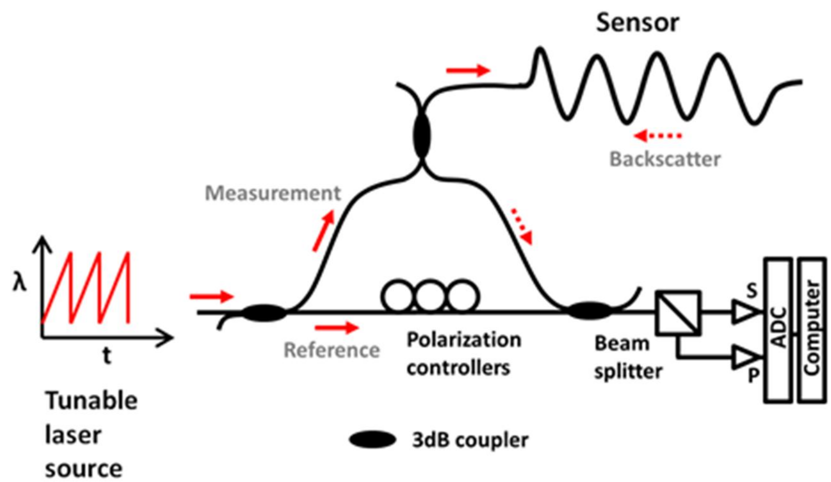

Figure 2: Basic OFDR Optical Network. Light from a tunable laser source (TLS) is swept through a range of optical frequencies. Light from a reference path interferes with light backscattered from reflectors on the measurement path. The interference pattern is measured by optical detectors and processed by algorithms that create a map of the reflections as a function of distance along the sensor.

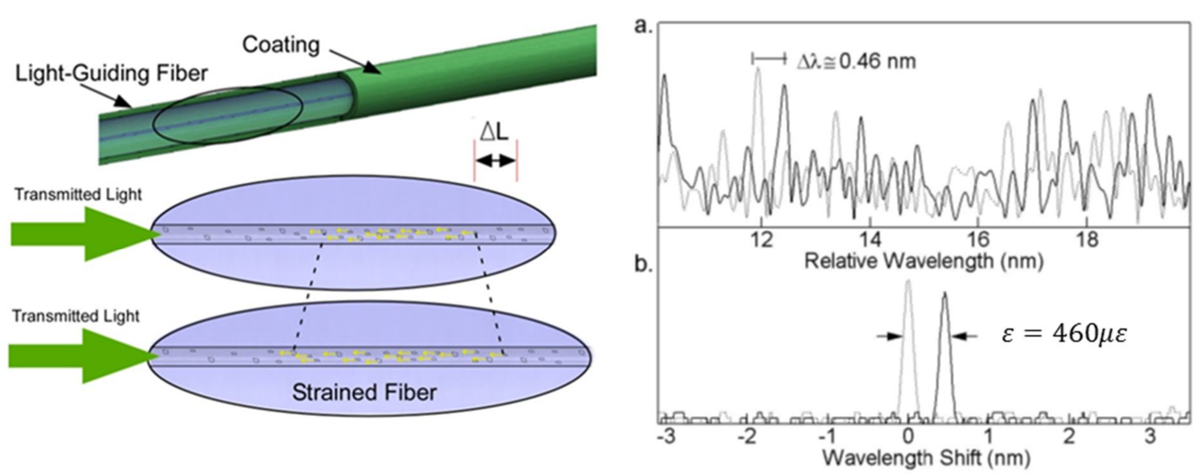

Figure 3: (Left) Mechanical representation of strain sensing mechanism. (Right)(a) Rayleigh scatter spectra along a 5 mm fiber segment for a strained (solid) and reference (dotted) scan. (b) Cross-correlation of the two spectra shows strain delta.

Luna leverages OFDR techniques to measure the spectral shift at every point along the length of each of the cores in a multicore optical fiber. This spectral shift is then converted to measured strain using known calibration coefficients appropriate to the fiber type. As shown in Figure 4, using this procedure, strain as a function of distance can be found along the entire length of each optical fiber core. These strains then combined to measure curvature, twist, and tension at every point along the sensing fiber.

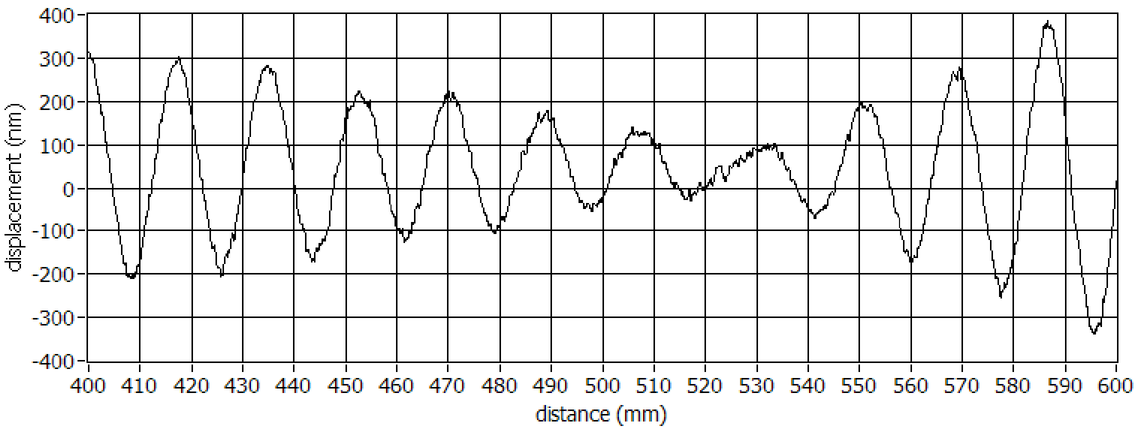

Figure 4: Using Rayleigh scatter, axial strain in an optical fiber is measured with sub-millimeter spatial resolution along the fiber.

C. OFDR Data Acquisition for Sensing Tethers

Luna's OFDR-based curvature and tension sensing technology traditionally operates on sensors less than 30 m in length. For tethered rover applications, longer sensing lengths were desired. The optical network and processing software of one of Luna's prototype data acquisition systems were modified to accommodate longer sensing lengths. This system supports simultaneous acquisition on four cores within the multi-core sensing fiber. To scan a 50 m tether, the system acquires more than 6 million data points per optical core, giving sensor spatial resolution of less than 50 micrometers along the entire fiber length. A scan with the laser interrogator takes approximately 35 milliseconds, and data processing requires approximately a minute. This prototype software has much room for optimization, so data processing time is expected to be reduced significantly in the future. The practical consequences of the prototype hardware and software used for these experiments are that the sensing tether can only be measured when it is static or nearly static during the 35 millisecond scan time, and that the sensing tether's update rate is not yet fast enough to be included as part of most automated feedback systems.

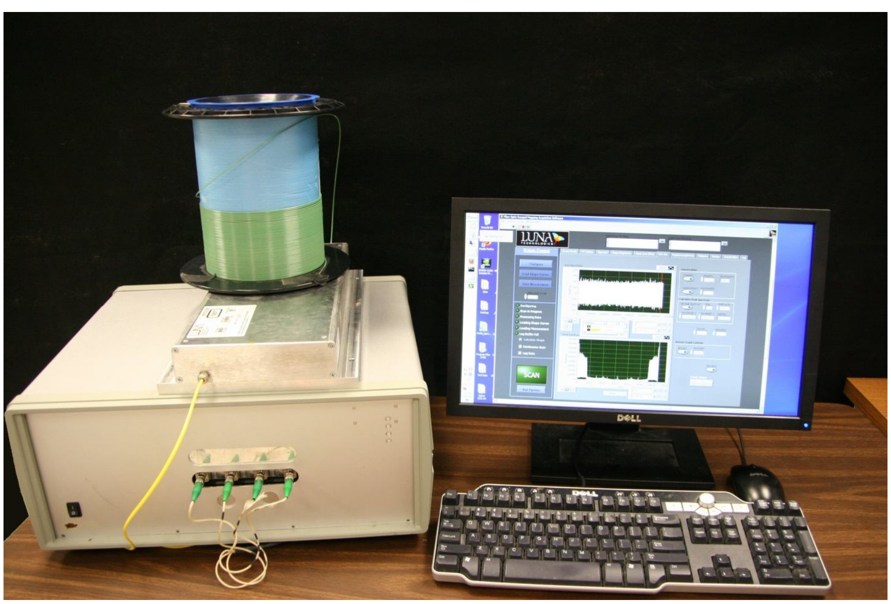

Figure 5: OFDR Acquistion system interrogating a 30 m multi-core sensing

IV. Tether Mechanical Design

The sensing fiber is only one part of the complete tether system. The sensing fiber was incorporated into a full cable that can withstand high tensile forces (up to 750N), be abrasion-resistant, and provide power and communication signals to the Axel rover. Luna worked with an outside cabling company to design and build two rounds of prototype tethers. In both rounds, the fundamental design remained the same, as shown in Figure 7. Four copper wires surround the center core, which contains the sensing optical fiber. Vectran strength members and a braided polyester cover finish out the cable. Note that the sensing fiber's small size does not increase the size of the tether cable.

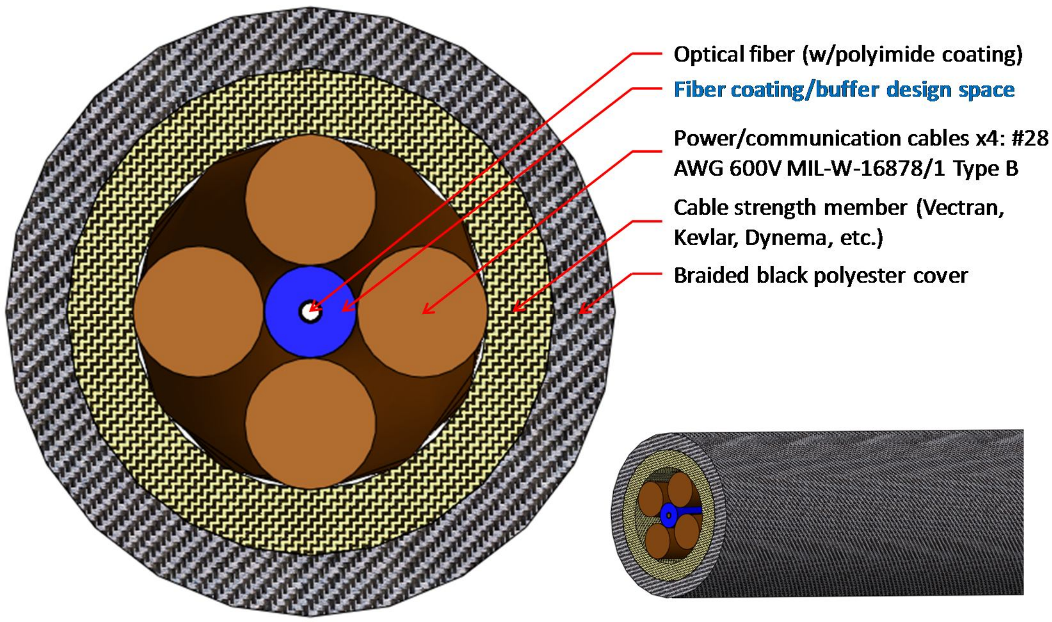

Figure 7: Cable design. Luna's sensing fiber replaces a nylon spacer that would occupy the central axis in a standard, non-sensing tether cable.

The first prototype tether was used to test two different possible buffer designs for the sensing fiber – a solid buffer and one with a softer inner layer. The buffer must meet several constraints. First, it must protect the fiber from damage during handling and the cabling process. Second, it must transfer strain from the cable to the sensing fiber to enable the tether's tension measurements. Third, it must preserve the quality of the OFDR signal even when subjected to the high radial stresses applied by the cable during deployment.

The selected buffer design consists of a rigid coating of Liquid Crystal Polymer (LCP) over a two-layer flexible acrylate undercoating. The hard coating protects the fiber while ensuring strain transfer, while the softer inner layers smooth out some of the point strains induced by the copper wires. Difficulties during the coating process lowered the yield of the cable, but a 50 m sensing tether was built for testing with JPL's Axel rover.

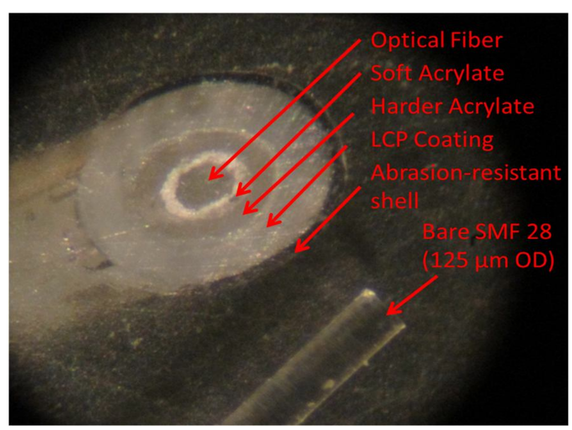

Figure 6: Polished end of a buffered single-core fiber shows the different coating layers that make up the buffer.

A hub clamp provides a temporary attachment point for mounting the distal end of the sensing tether to Axel, strain relief, and a place to house the optical and electrical components needed to translate the optical communication link in the sensing fiber back into an electrical signal that could pass through Axel's slip ring and in to its embedded electronics. The hub clamp that was used for final testing is shown on the Axel rover in Figure 8.

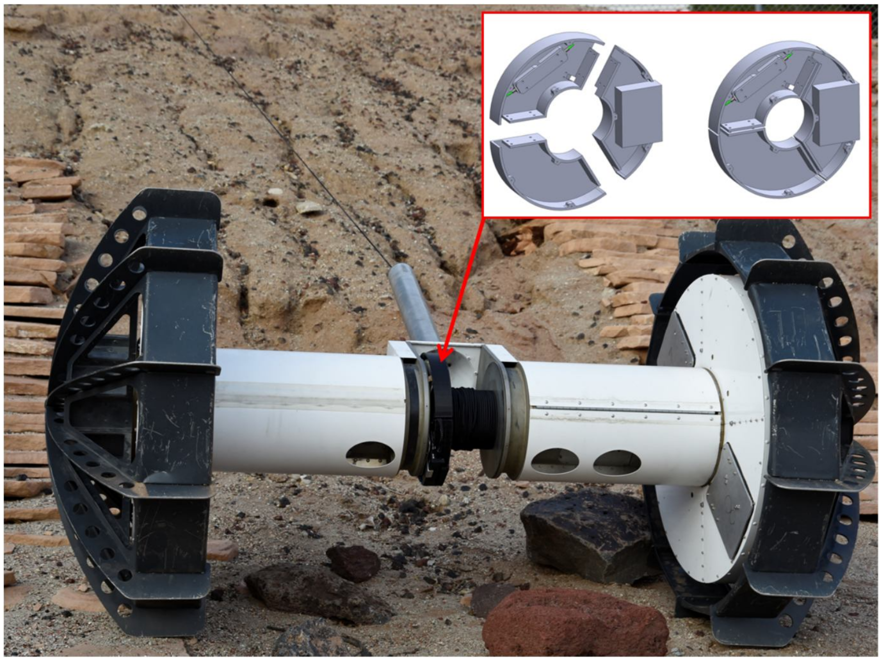

Figure 8: The 50-m sensing tether prototype installed on JPL's Axel Rover. The hubclamp provides strain relief and a place to house the electrical and optical components needed to transfer power and communications signals from the tether to the rover.

Future designs will incorporate this functionality into the spool design.

V. Tether Calibration

The 50-m sensing tether was calibrated prior to field testing. The calibration process had several different stages: Pre-tensioning was designed to exercise the newly constructed cable to eliminate the hysteresis associated with the cable's break-in period. Tension calibration measured the relationship between externally applied tension and the strain measured by the sensor at the cable's center. A reference scan of the sensor's optical cores in a nominally straight configuration was used to establish a baseline for the curvature and twist measurements. Finally, a set of scans in configurations with known twist and cuvature states were used to measure the relationships between the strains on the center and outer optical cores and curvature and twist.

A. Pre-tensioning and tension calibration

The tension system shown in Figure 9 was designed and built to accurately apply known amounts of tension to the cable in 24m-long sections. The cable section is anchored on both ends with friction clamps that can withstand more than 900N of tension without damaging the cable. Three pulleys reduce the area needed to apply tension to a long section of the cable, and provide mechanical advantage to the tensioning mechanism. A load cell in line with the central pulley monitors the tension, and a hand-crank is used to set the tension.

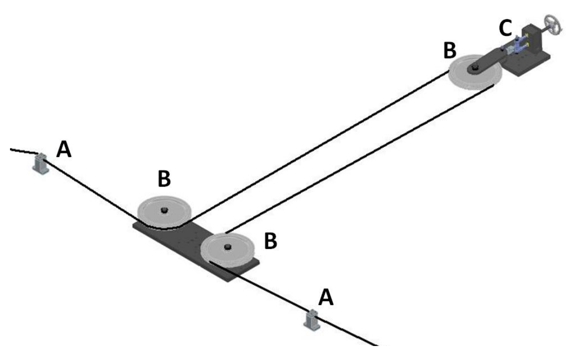

Figure 9: Model of tension system with anchor points (A), pulleys (B) and calibrated strain gage for monitoring tension (C).

With a goal of measuring tensions up to 250 N and surviving tensions up to 750 N, the 50-m tether was pre-tensioned to more than 850 N in three overlapping 24 m sections and held for at least two hours. As the cable stretched and relaxed, the tensioner had to be adjusted frequently to remove slack and maintain the 850 N tensile load. The multi-core sensing fiber was monitored using OFDR techniques during the pretensioning process to ensure that the fiber did not break.

Following the pre-tensioning cycle, the first 24 m of the sensor was used to perform a tension calibration. It was assumed that the relationship between applied tension on the cable and measured strain in the sensing fiber would remain constant along the length of the sensor. A linear relationship was found between the tension applied to the cable and the uncalibrated strain measured on the center core of the sensing fiber.

B. Curvature and twist calibration

The sensing tether was then placed in a variety of constrained configurations and all four optical cores were scanned in several known configurations to generate a data set for establishing the relationships between the distributed strains on the central and outer optical cores and the tether's distributed radius of curvature and twist. These configurations include a planar spiral, a straight line, and several circles with known radii.

VI. Testing

A. Preliminary Testing

The 50-m tether was installed on one of the prototype Axel rovers. The hub clamp was installed, and the distal end of the tether was attached to it. The electrical connections for the Ethernet signal were routed away from Axel's wireless router and instead sent through the slip ring to the optical to Ethernet converter. This connection was tested, and it was shown that the Axel could be controlled using only communication through the optical fiber within the tether, without using the wireless connection or the copper wires in the tether. The rover was controlled using communication through the optical fiber for the rest of the testing. With all of the distal end connections established, the tether was spooled onto Axel's hub, and the sensing tether was interrogated to make a measurement of the setup, as shown in Figure 10. The measured curvature is as expected – the tether is in a tight bend (high curvature) at about

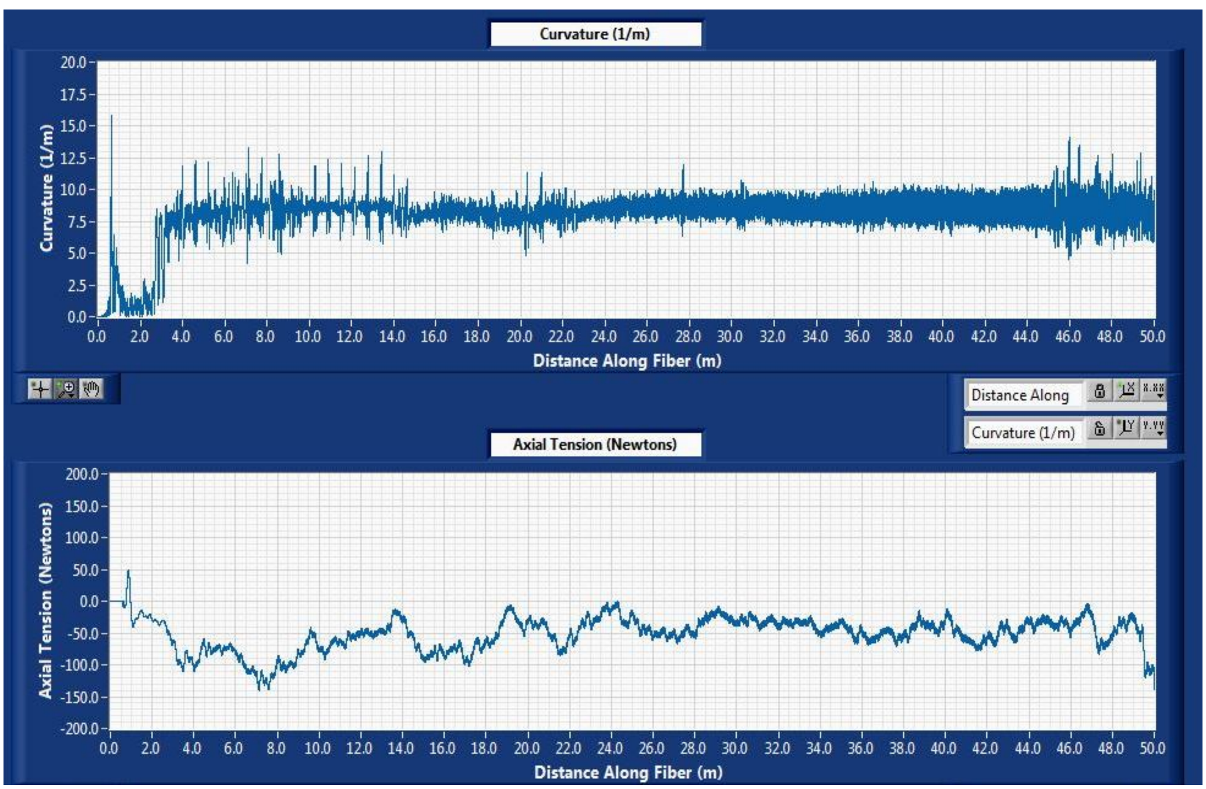

Figure 10: Test scan of the sensing tether with most of its length spooled on Axel's central hub. Note that the curvature (top) is nearly constant from where it hits the spool at 3m to its end at 50m. The tension is assumed to be residual strain imparted by the spooling process.

0.5 m from its start, where it entered the Axel rover's boom arm. The next meter is straight, where the sensing tether runs down the centerline of the boom arm. Finally, from approximately 3 m to 50 m, the tether shows nearly constant curvature of roughly 8 m^{-1}, which corresponds to a bend radius of 12.5 cm. Axel's central hub has in radius of 4.2 cm, and the spooling fiber quickly added thickness. The difference is likely due to an error in calibration. The local spikes in the first 14 m of the sensing tether's curvature measurement are likely due to uneven winding of the tether on the spool.

B. Testing at JPL's MarsYard

The JPL Mars Yard is a simulated Martian landscape used to test different robotic prototypes. This facility provides a large test area and an outdoor environment to test different robotic platforms. The soil characteristics are matched to some regions on Mars, and the rock colors, sizes and distribution are intended to match images from NASA's Martian missions[5]. The Axel rover with the 50-m sensing tether was taken to the Mars Yard for testing. The base station was established on a balcony above a rocky slope. The tether was run loosely from the base station to an anchor point where it was tightly clamped. From there, it ran down the slope to the rover. The rover was driven to the top of the slope, using the tether as a guide and pull cable. The sensing tether made measurements of tension and curvature during the ascent (Figure 11).

Figure 11: (Top) The rover ascending the slope in the Mars Yard. (Bottom) The base station displaying measurements of the curvature and tension in the cable as the rover navigates the terrain.

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[5] https://www-robotics.jpl.nasa.gov/facilities/facility.cfm?Facility=14

From the top of the slope, the rover was driven back down the slope on a diagonal path that intentionally snagged the tether on a pile of rocks. Shortly after the tether snagged, Axel's wheels bogged down in sand and rock. Several attempts to move resulted in sharp jerks on the tether. As seen in Figure 12, these sharp jerks put a very high amount of tension on the cable, particularly at the pinch point where the tether was snagged. The sensing tether reports approximately 500 N of tension along the region of the tether leading from the anchor point (6 m) to the rover (16 m). There is a tension spike up to approximately 700 N where the tether contacts the rock, at 11 m. For reference, the tether is rated to sense through up to 250 N, and to survive up to 750 N. It is suspected that during the jerking motions, transient tensions exceeded 750 N, but acquisition system is currently unable to make measurements while the tether is moving. In the section of tether on the spool and under low tension (16m and

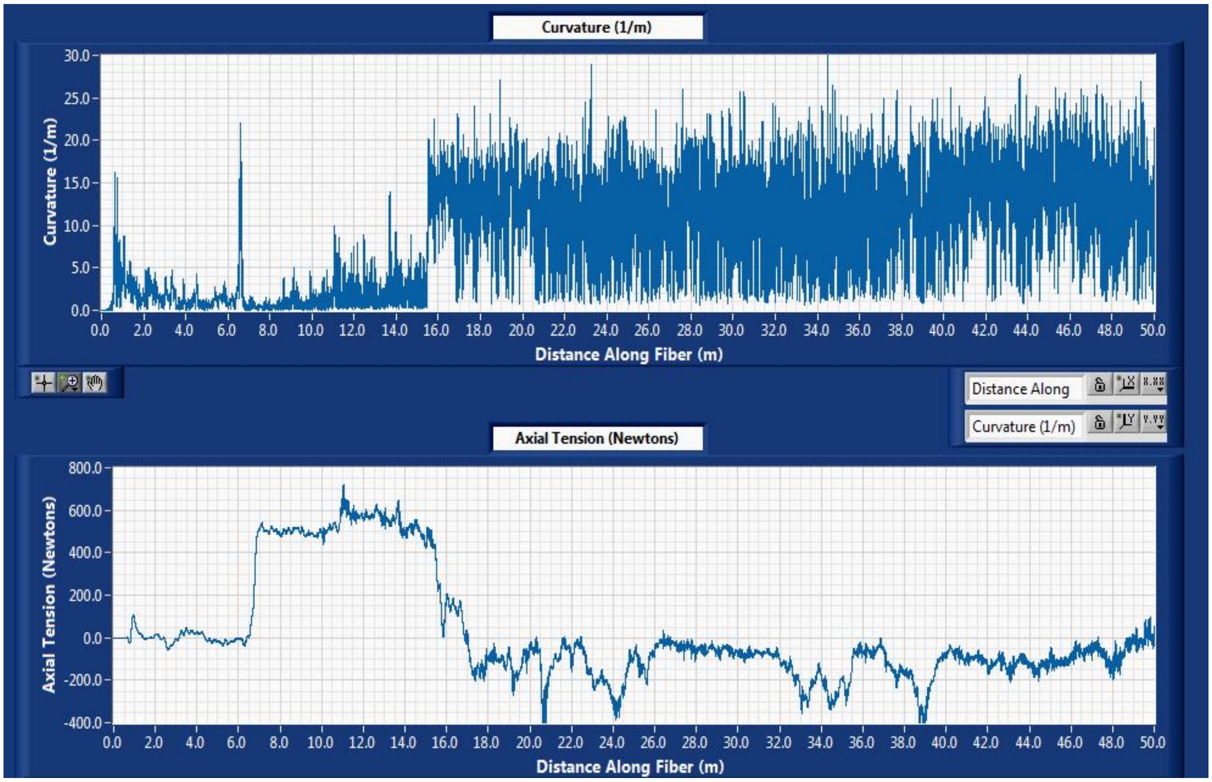

Figure 12: Scan of sensing tether with tether snagged on rock. Curvature (top) and tension (bottom) show the clamp point at 6 m, then high tension to the Axel rover, at 16 m. A tension spike at 11 m, with a corresponding jump in the curvature signal, shows where the cable is snagged on a rock. Vibration in the tether has degraded the quality of the curvature measurement, but the curvature of the tether on the spool is still visible from 16m to 50 m.

beyond) there are some false negative tension, or compression, readings. These are assumed to be the result of actual compression on the sensing fiber, induced by the hysteresis of the copper wires and the tight bend radius of the tether.

Once the rover freed its wheels from the sand and rocks, it continued its descent down the slope. Near the bottom, another measurement of the tether was taken. When the rover reached the bottom of the slope, it was instructed to climb again. As it began climbing, it again pulled on the tether. This time, the tether snapped at the snag point, ending the testing.

VII. Conclusions

A. Tether Performance

Overall, testing of the sensing tether prototype with the Axel rover was a success, even though it ended with a break in the tether. Luna's sensing technology was able to measure the curvature and tension along the tether as the rover navigated difficult terrain. As Figure 13 shows, relevant features, such the tether anchor point, a rock snag, the cable's entrance into the rover's arm, and rover's central hub, can all be identified by their combination of tension and curvature signatures. The tether mechanically failed at the precise location where excessively high tensions and tight curvature where observed. The tether's high-resolution feedback provided us with a warning of the pending mechanical failure.

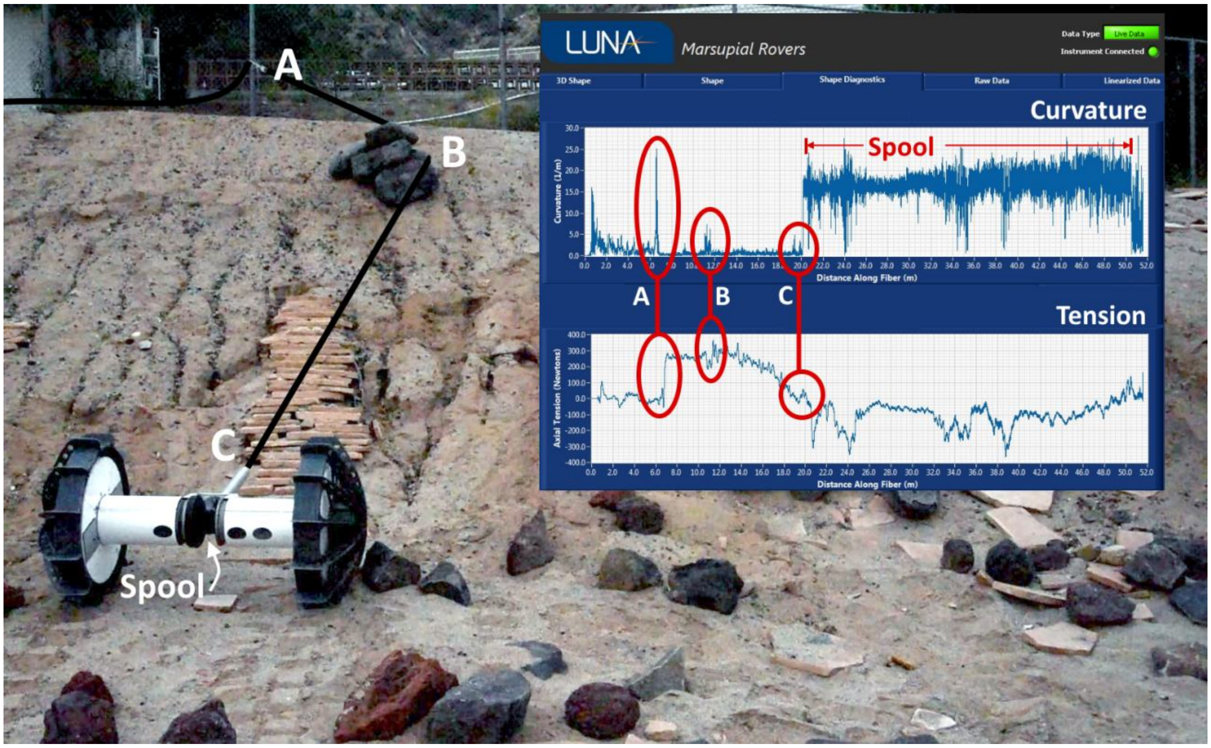

Figure 13: As the rover descends a steep slope, Luna's sensing tether shows several points of interest: (A) The tether is clamped to an anchor point. The curvature shows a tight bend and the tension shows a sharp increase. (B) The tether is snagged on a rock. A local curvature event marks the bend at this location, and a rapidly changing tension feature shows that the tether is wedged tightly. (C) A small curvature feature marks the point where the tether enters Axel's boom arm. (Spool) The elevated curvature for the distal end of the tether's length shows where the bulk of the tether is spooled around Axel's central hub.

Examination of the broken tether shows that significant abrasion occurred where the tether was wedged in the rocks. The rocks used in this test were manufactured fiber glass rocks where parts of the highly abrasive surface were in contact with the tether. This, combined with the high tensions that occurred while the rover bounced while trying to free its wheels on the descent probably weakened the tether at this pinch point, causing it to fail the next time high tension was applied, as the rover began its second ascent of the slope.

In the robotics world, tethers are often viewed as a necessary evil. Bulky, delicate, and often in the way, tethers supply power and data to systems not large enough to stand on their own. The testing conducted at JPL with the new sensing tether prototype has demonstrated this technology's potential to change the equation, turning tethers into an asset, another sensor in a rover's toolbox that can be used to measure the environment and provide crucial information for feedback and control.

B. Future Work

Testing also suggested areas of further development for this technology. Algorithm development could improve performance in the face of moderate motion or vibration, removing the need to pause the rover and wait for the cable to stop moving before taking a measurement and making it possible to measure peak transient loads. Improvements to the acquisition system and processing software could support faster update rates that would improve the user experience and increase the utility of the data. Packaging improvements to minimize or eliminate the hysteresis in the tension measurement could eliminate the local false tension features that are due to the bending of the tether.

Some of these features appear when the tether is bent, and they do not necessarily disappear when the tether is straightened again. This is assumed to be due to memory in the copper wires that surround the sensing fiber. Finally, alternate materials for the tether's outer jacket could improve its abrasion resistance.

Acknowledgments

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